Paper

RADIATION DOSES TO LOCAL POPULATIONS NEAR NUCLEAR WEAPONS TEST SITES WORLDWIDE

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Abstract—Nuclear weapons testing was conducted in the atmosphere at numerous sites worldwide between 1946 and 1980, which resulted in exposures to local populations as a consequence of fallout of radioactive debris. The nuclear tests were conducted by five nations (United States, Soviet Union, United Kingdom, France, and China) primarily at 16 sites. The 16 testing sites, located in nine different countries on five continents (plus Oceania) contributed nearly all of the radioactive materials released to the environment by atmospheric testing; only small amounts were released at a few other minor testing sites. The 16 sites discussed here are Nevada Test Site, USA (North American continent), Bikini and Enewetak, Marshall Islands (Oceania); Johnston Island, USA (Oceania), Christmas and Malden Island, Kiribati (Oceania); Emu Field, Maralinga, and Monte Bello Islands, Australia (Australian continent); Mururoa and Fangataufa, French Polynesia (Oceania), Reggane, Algeria (Africa), Novaya Zemlya and Kapustin Yar, Russia (Europe), Semipalatinsk, Kazakhstan (Asia), and Lop Nor, China (Asia). There were large differences in the numbers of tests conducted at each location and in the total explosive yields. Those factors, as well as differences in population density, lifestyle, environment, and climate at each site, led to large differences in the doses received by local populations. In general, the tests conducted earliest led to the highest individual and population exposures, although the amount of information available for a few of these sites is insufficient to provide any detailed evaluation of radiation exposures. The most comprehensive information for any site is for the Nevada Test Site. The disparities in available information add difficulty to determining the radiation exposures of local populations at each site. It is the goal of this paper to summarize the available information on external and internal doses received by the public living in the regions near each of the mentioned nuclear test sites as a consequence of local fallout deposition.

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INTRODUCTION

ATMOSPHERIC NUCLEAR weapons tests conducted at various sites worldwide between 1946 and 1980 exposed members of the public, members of the military, and test personnel to ionizing radiation. While some of the exposure was direct (prompt neutron and gamma), more individuals were exposed as a result of the "fallout" of radioactive debris from the atmosphere following the tests. Estimates of exposures and radiation absorbed doses resulting from "local fallout" from the most significant nuclear test sites worldwide are discussed in this paper. Radiation exposures received as the result of explosions at Hiroshima and Nagasaki are not discussed here, because those explosions were not "tests" in the conventional meaning of the word, nor was the primary health impact of those explosions a result of fallout deposition. It should be pointed out that in this paper and in general there is not a clear distinction between "local" and "regional" fallout. In this paper, "local" is considered to be within a distance of 500 km from the test site, although occasionally the region out to about 1,000 km distance is discussed, depending on the availability of information. Exposures received by members of the public as a consequence of the extended "regional" and "global fallout" via tropospheric air movement or ~~strato~~spheric circulation are discussed in this issue by Bouville et al. (2002).

At some nuclear tests sites, the available information is limited to a description of the test events, i.e., date, time, yield, weapon placement (surface, tower, balloon, etc.), and, occasionally, atmospheric conditions and concentrations in selected environmental media (e.g., pasture grass, cows' milk, etc.). For those sites, there is little information about public or test personnel exposures, but at nearly all test sites, there have been allegations of exposures of military and test personnel and often times of small groups of remotely located members of the public. In many of these cases, the evidence of exposure is not substantial but anecdotal in nature. That situation is particularly acute for many of the oceanic test sites. Only at a few of the test sites, in particular the Nevada Test Site (NTS) in the United States, has there been considerable effort expended towards estimating exposures of the public and military/test personnel.

In this paper, a review is made of reported exposures and doses to members of the public from 16 nuclear test sites located in 9 different countries. Only brief information on exposure of military and/or test personnel is included. The discussion is ordered by the year in which

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testing first began in each country:

1. *1946*: Bikini and Enewetak Atolls, Marshall Islands
2. *1949*: Semipalatinsk, Kazakhstan
3. *1951*: Nevada Test Site, United States
4. *1953*: Emu Field, Maralinga, and Monte Bello Island, Australia
5. *1955*: Novaya Zemlya (islands) and Kapustin Yar, Russia
6. *1957*: Christmas Island and Malden Island, Kiribati
7. *1958*: Johnston Atoll, United States
8. *1960*: Reggane, Algeria
9. *1964*: Lop Nor, China
10. *1966*: Mururoa and Fangataufa Atolls, French Polynesia.

There are a number of published reviews that provide basic statistics of nuclear testing worldwide, e.g., Warner and Kirchmann (2000, in particular), Bennett et al. (2000), UNSCEAR (2000), and Beck and Bennett (2002). Other papers have focused on doses received (Bouville et al. 2000). For certain testing sites, there have been books and issues of journals entirely devoted to the testing programs and their consequences (Health Physics 1990, 1997; IPPNW 1991).

Readers will note in the above references some variations in the number of tests reported as well as the total explosive yield (MT TNT equivalent). For example, Bennett et al. (2000) report 541 tests, while UNSCEAR (2000) reported 543 above ground explosions that include two combat detonations. Table 1 provides a summary of information about the test sites considered here including the country and continent in which the tests took place, the country responsible for the tests, the number of tests and total yield at each site, and the climatic zone/environment type. For each test site, the available information on external and internal doses received by the "local" populations will be summarized. The estimates of doses in the literature from external irradiation have been reported in various units including free-in-air exposure (roentgen), average absorbed dose over the entire body (gray), effective dose equivalent (sievert), or effective dose (sievert). Primarily because the gamma ray energies emitted from many radionuclides are energetic enough to completely penetrate the body, the external doses to most tissues and organs are about the same. Hence, it is justified here to make an approximation that the effective dose (sievert) or the effective dose equivalent (sievert) is numerically equal to the absorbed dose for most organs (gray) or to the average absorbed dose over the entire body (gray). For the range of gamma energies usually encountered from fallout, the conversion from exposure to effective dose, without taking into account shielding by buildings, is about 0.0066 Sv R^{-1} (0.75 Sv Gy^{-1} × 0.01 Gy rad^{-1} × 0.875 rad R^{-1}) for adults and is about 30% higher for young children (NCRP 1999) than for adults. In order to facilitate the comparison of the results presented in different units in the various cited reports, the doses from external irradiation have all been expressed in this paper in terms of average absorbed dose over the entire body (gray) assumed to be numerically equal to the effective dose or effective dose equivalent (sievert). The doses from internal irradiation are also expressed in this paper in terms of absorbed dose (gray) to the organ or tissue of interest (thyroid or red bone marrow, primarily).

Fig. 1 presents the annual explosive yields (MT TNT equivalent) of the tests at each of the test sites (Bikini and Enewetak are grouped, as are Christmas and Malden Island, and Mururoa and Fangataufa). The years in which testing began at the various sites could be grouped into the years 1946 through 1953 (top panel, Fig. 1), 1955 through 1960 (middle panel, Fig. 1), and 1964 through 1966 (bottom panel, Fig. 1). The remaining discussion follows that chronology.

REVIEW OF TEST SITES AND DOSES RECEIVED

The nuclear test sites where atmospheric weapons tests were conducted were located in Asia, Australia, Africa, Europe, Oceania, and North America [see Beck and Bennett (2002) for a map of the locations]. Ten of the sixteen sites were located in Oceania/Australia. For that reason, Fig. 2 is presented to show additional detail on the locations of the oceanic test sites. Of those, only Bikini, Enewetak, Johnston Island, and Christmas Island were in the northern hemisphere. Islands (or atolls), in general, were preferred locations for testing because of their remoteness from mainland population centers. Nine of the 16 testing sites were located on islands.

Bikini and Enewetak Atolls, Marshall Islands (United States test site)

Part of Oceania, and located in the equatorial waters of the mid-Pacific, the Marshall Islands were a trust territory of the United States until 1986. Two nuclear test sites were located in the Marshall Islands: Bikini Atoll and Enewetak Atoll. Nuclear testing began in the Marshall Islands in 1946 and continued through 1958. The total explosive yield of the tests in the Marshall Islands was about 109 MT with 77 MT at Bikini and 32 at Enewetak (Simon and Robison 1997).

Neither the Bikini nor Enewetak Atoll test sites in the Marshall Islands were inhabited during the testing years; populations from both sites were moved for purposes of safety before the testing began (see Simon 1997 and Niedenthal 1997 for historical perspectives). Hence, resident civilian populations were not exposed to prompt radiation from the detonations themselves, although press and other official spectators did observe the two CROSSROADS (1946) explosions from relatively close distances. Military and test personnel that participated in some of the events, in particular, Operation CROSSROADS, likely received some exposure from prompt radiation and from handling radioactive debris during cleanup operations. Little information is available, however, on exposures from CROSSROADS.

Native populations lived in the Marshall Islands at distances ranging from less than 200 km to over 1,000

Table 1. A summary of atmospheric nuclear testing at the 16 primary test sites ordered by first year of testing (data from Bennett et al. 2000; UNSCEAR 2000) and grouped by country where the testing was conducted.

Test sites	Continent of test site(s)	Present-day country where testing took place	Country responsible for testing	Years of atmospheric nuclear testing	Environment type/ Climatic zone	Number of surface + atmospheric tests	Yield (MT TNT equivalent)	Total yield (MT) by continent
Bikini (B) and Enewetak (E) Atolls	Oceania	Republic of the Marshall Islands	USA	1946, 1954, 1956, 1958 (B); 1948, 1951, 1952, 1954, 1956, 1958 (E)	tropical island	23 (B) + 42 (E)	76.8 (B) + 34.6 (E)	
Semipalatinsk Test Site	Asia	Republic of Kazakhstan	USSR	1949, 1951, 1953–1958, 1961	steppe	116	6.6	
Nevada Test Site	North America	United States of America (USA)	USA	1951–1953, 1955, 1957, 1958, 1962	inland desert	86	~1	
Emu Field (E), Maralinga (M), and Monte Bello Islands (MB)	Australia	Commonwealth of Australia	UK	1953 (E); 1953, 1956, 1957 (M); 1952 and 1956 (MB)	inland desert (E, M)/ arid island (MB)	12	<0.2	
Novaya Zemlya (NZ) and Kasputin Yar (KY)	Europe	Russian Federation (Russia)	USSR	1955, 1957, 1958, 1961, 1962 (NZ); 1957, 1958, 1961, and 1962 (KY)	arctic tundra (NZ), steppe (KY)	91 (NZ) + 10 (KY)	239.6 (NZ) + ~1 (KY)	
Christmas Island (CI) and Malden Island (MI)	Oceania	Republic of Kiribati	USA and UK	1957, 1958 (CI and MI, UK); 1962 (CI, USA)	tropical island	24 (US[a]) 9 (UK[b])	23.3 (US) 7.9 (UK)	Africa: ~0.1
Johnston Atoll	Oceania	Unincorporated territory of USA	USA	1958, 1962	tropical island	12	~21	Asia: ~28
Reggane	Africa	Democratic and Popular Republic of Algeria	France	1960, 1961	inland desert	4	<0.1	Europe: ~240
Lop Nor	Asia	People's Republic of China	China	1964–1974, 1976–1978, 1980	inland desert	22	~21	North America: ~1
Mururoa and Fangataufa Atolls	Oceania	Territory of French Polynesia (France)	France	1966–1968, 1970–1974	tropical island	41	~10	Oceania: ~171
Miscellaneous sites [2 tests elsewhere in Pacific (USA), 3 in South Atlantic (USA), 2 at Totsk, Tralsk (USSR)].						492[c] Total	~440	~440

[a] Christmas Island only.
[b] Christmas and Malden Islands.
[c] Totals in other references differ due to inclusion of tests at miscellaneous sites [1 in New Mexico (US), 4 elsewhere in the Pacific (by US), 3 in South Atlantic (by US), 2 at Totsk, Tralsk, Russia (by USSR), 2 combat explosions in Japan (by US), and 39 safety trials (22 by US, 12 by UK, and 4 by France)].

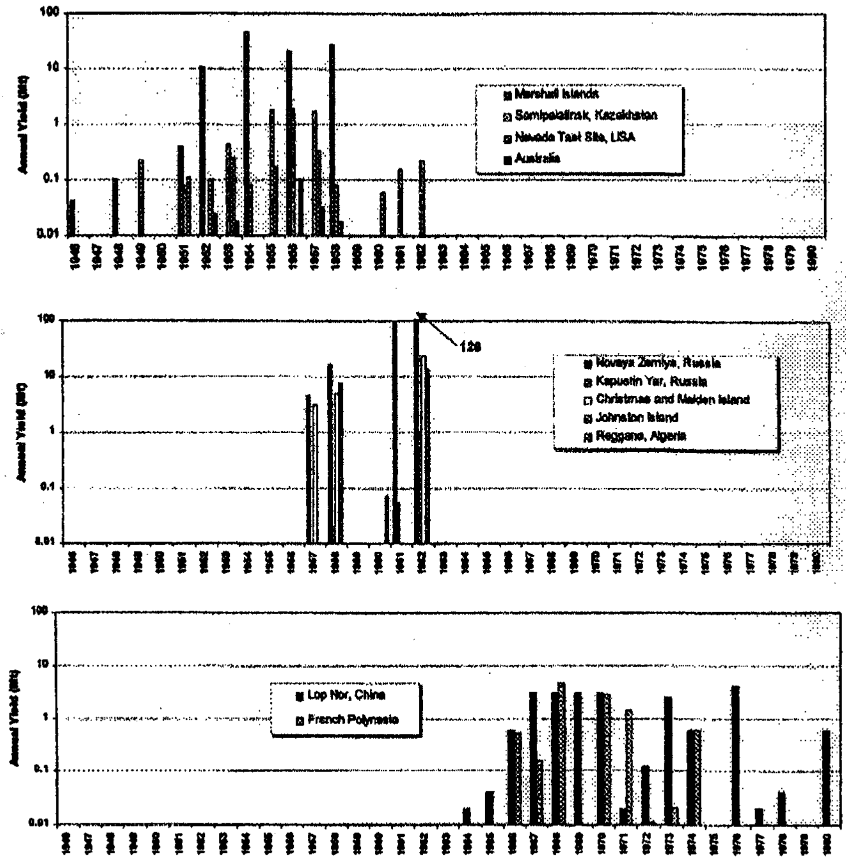

Fig. 1. Time and explosive yield history of atmospheric testing worldwide.

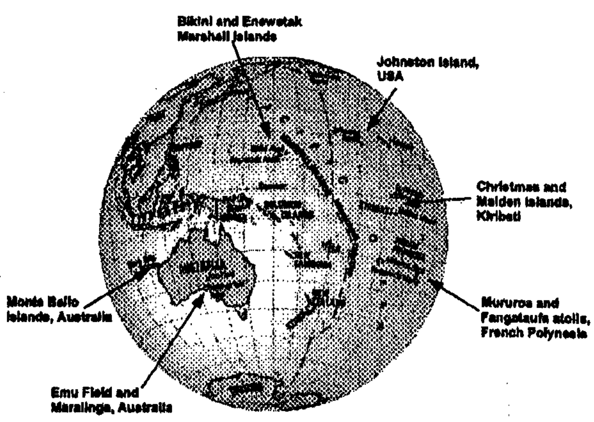

Fig. 2. Locations of oceanic nuclear testing sites.

km [see Health Physics (1997) for a map of atolls]. The nearly 20 inhabited atolls of the Marshall Islands are located at distances that could have received "local fallout." However, except for the well-publicized 1954 accidental exposures accompanying the detonation of the BRAVO test, there is little or no documentation of other significant exposures taking place there. The BRAVO test resulted in significant fallout deposition and consequent exposures and doses to small populations living on Rongelap and Utrik Atolls, a small group of Rongelapese visiting Ailinginae Atoll, 28 United States weathermen resident on Rongerik, and sailors on a Japanese fishing vessel that strayed into the adjoining waters of Bikini Atoll just prior to the test.

The BRAVO test was part of Operation CASTLE, a series of six large tests in 1954. Marshallese were exposed at a number of atolls as a result of the CASTLE series (Breslin and Cassidy 1955), though all atolls received much less exposure than did Rongelap. For example, Utrik received only about 10% of the exposure received at Rongelap, while other atolls received only a fraction of the exposure at Utrik. The other six test series (CROSSROADS in 1946, SANDSTONE in 1948, GREENHOUSE in 1951, IVY in 1952, REDWING in 1956, and HARDTACK I in 1958) may have added some additional exposure to residents of the Marshall Islands, but there is no indication from any of the available data that there were any large or significant exposures from any series but CASTLE.

The remainder of this section summarizes doses received from fallout originating primarily from the BRAVO test and, in some cases, the entire CASTLE series. For the

Table 2. A summary of dose estimates from atmospheric nuclear testing at the 16 primary test sites (see Table 1). Dash (—) means no information was found.

Test site	Tests, test series, or total of all tests	Locations of potential exposures (cities, villages, islands, etc.)	Average external whole body dose (mGy)	Thyroid dose to children (1–2 y age) (Gy)	Approximate number of people exposed	Estimate of collective external whole-body dose (person-Gy)	Estimate of collective thyroid dose (children 1–2 y) (person-Gy)	Literature references
Bikini and Enewetak Atolls, Marshall Islands	BRAVO test (1 March 1954)	Rongelap Atoll	1,900	50	64	122	—	Lessard et al. (1985), Conard (1975)
		Rongerik Atoll	810	(no children)	28	23	—	"
		Ailinginae Atoll	1,110	13	18	20	—	"
		Utrik Atoll	110	6.7	157	17	—	"
"	CASTLE series (1954)	*Selected atolls:*						Breslin and Cassidy (1955), Population data: RMI (1989)
		Ailinglaplap	1.7	—	1300	2.2	—	
"	"	Ailuk	41	—	400	16.4	—	"
"	"	Kwajalein	8.2	—	1,300	10.7	—	"
"	"	Likiep	14.5	—	640	9.3	—	"
"	"	Majuro	3.1	—	3,400	10.5	—	"
"	"	Wotje	16.8	—	360	6.0	—	"
"	"	All Atolls	13.6	—	14,000 (all atolls)	191 (all atolls)	—	"
Semipalatinsk, Kazakhstan		*Selected villages/cities:*						
	29 August 1949	Dolon	900	1–2.2	850	765	35–77	Stepanov et al. (2001)
	All tests	"	2,200		306	2,000		Bouville et al (2000)[a]
"	29 August 1949	Kanonerka	210	0.35–0.7	2400	500	35–70	Stepanov et al. (2001)
	All tests	"	840		1200	1000		Bouville et al. (2000)[a]
"	24 September 1951	Kaynar	70	3–3.8	450	32	54–68	Stepanov et al. (2001)
"	12 August 1953	Sarzhal	180	—	630	110	—	Stepanov et al. (2001)
	All tests	"	1200		830	970		Bouville et al. (2000)[a]
Semipalatinsk, Kazakhstan	12 August 1953	Kara-Aul	130	—	2400	310	—	Stepanov et al (2001)
	All tests	"	360		2300	240		Bouville et al. (2000)[a]
"	24 August 1956	Ust-Kamenogorsk	56	—	130,000	7,300	—	Stepanov et al (2001)
"	24 August 1962	Semipalatinsk (city)	0.2	—	145,000	30	—	Stepanov et al (2001)
	All tests	"	3.7		163,000	610		Bouville et al (2000)[a]
"	44 tests	Altai region (Russia)—58 raions	18.6	—	2,200,000	41,200	—	Shoikhet et al. (1999)
Nevada Test Site, USA	All tests	ORERP Phase I area (see text)	2.8	—	180,000	500	—	Anspaugh et al. (1990)

Table 2. Continued.

Test site	Tests, test series, or total of all tests	Locations of potential exposures (cities, villages, islands, etc.)	Average external whole body dose (mGy)	Thyroid dose to children (1–2 y age) (Gy)	Approximate number of people exposed	Estimate of collective external whole-body dose (person-Gy)	Estimate of collective thyroid dose (children 1–2 y) (person-Gy)	Literature references
″	″	ORERP Phase I + II areas (see text)	0.6	0.007 (all days)	20,000,000	12,000	140,000 (all ages)	Anspaugh (2000), Whicker et al. (1996)
″	″	St. George, Utah	15.8	0.25 (all ages)	4,900	77.4	1,200 (all ages)	Whicker et al. (1996), Beck and Krey (1983)
Emu Field, Maralinga, and Monte Bello Islands, Australia		*Selected population centers:*						
	All test series 1952–1957	Broome	0.18	0.020 (all ages)	3,340	0.60	66.8 (all ages)	Wise and Moroney (1985)
″	″	Noonkanbh	0.16	0.018 (all ages)	75	0.01	1.4 (all ages)	″
″	″	Onslow	0.10	0.011 (all ages)	543	0.06	6.0 (all ages)	″
″	″	Pt. Hedland	0.23	0.025 (all ages)	1,367	0.32	34.2 (all ages)	″
Novaya Zemlya and Kasputin Yar, Russia	All tests	—	—	—	—	—	—	See text.
Christmas and Malden Islands, Kiribati	All tests	Nearby islands/atolls.	—	—	—	—	—	See text.
Johnston Atoll, USA	All tests	None (Hawaii is closest at 1330 km)	—	—	—	—	—	See text.
Reggane, Algeria	All tests	Very few inhabited locations near to test site (primarily village of Reggane)	—	—	—	—	—	See text.
Lop Nor, China		*Selected towns and villages:*						
	All tests	Anxi	0.02	—	60,000	1.2	—	Zheng et al. (1996)[b], UNSCEAR (2000)
″	″	Yumenzhen	0.03	—	159,000	4.8	—	″
″	″	Jinta	0.11	—	99,000	10.9	—	″
″	″	Jiayuguan	0.11	—	89,000	9.8	—	″
″	″	Shenyang	—	0.022	—	—	—	Liu and Zhu (1996)[c], Bouville et al. (2000)
″	″	Xining	—	0.02	—	—	—	″
″	″	Lanzhou	—	0.025	—	—	—	″
Mururoa and Fangataufa Atolls, French Polynesia		*Atolls/islands throughout archipelago*						
	2 July 1966	Gambier Islands	3.4	—	40	0.14	—	Bourges (1997), UNSCEAR (2000)
″	8 August 1971	″	0.9	—	68	0.061	—	″
″	2 July 1967	Tureia Atoll	0.7	—	516	0.36	—	″
	12 June 1971	″	0.9	—	545	0.49	—	
″	17 July 1974	Tahiti	0.6	0.0068	84,000	50.4	11 (assumes 2% of population is 1–2 y of age)	UNSCEAR (1979), Bouville et al. (2000)

[a] Data derived originally from G.D. Vdovichenko, Dept. of Radiation Hygiene of the Ministry of Kazakhstan, 480008, Alamata, Kazakhstan.
[b] Zheng Y, Yongze M, Jiangchen L. Long range atmospheric transportation and fallout of nuclear test debris. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 199
[c] Liu Y, Zhu C. Environmental contamination and health effect from iodine-131 in fallout in China. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 19–21

Rongelap and Utrik populations exposed to BRAVO fallout, their exposures occurred before their evacuation, 1 to 2 d following the test. Further detail on those events can be found in several publications including Breslin and Cassidy (1955), Lessard et al. (1985), Robbins and Adams (1989), Conard (1992), Cronkite et al. (1997), Eisenbud (1997), Simon (1997), and Bouville et al. (2000).

Exposures at Rongelap, Utrik and other atolls. The thermonuclear device, code-named BRAVO, was exploded on Bikini Atoll on 1 March (local time) 1954, with an explosive yield of 15 MT. An unexpectedly high yield, as well as wind-shear conditions, resulted in heavy fallout to the east of Bikini rather than over open seas to the north and west. About 3 to 6 h after the explosion, the radioactive cloud deposited particulate, ash-like material on 64 inhabitants of Rongelap Atoll located about 200 km eastward of the detonation site, on 18 other Rongelapese who were fishing and gathering copra at nearby Ailinginae Atoll, and on 23 fishermen on a Japanese vessel, the Lucky Dragon No. 5 (Conard 1980; Lessard et al. 1985; Robbins and Adams 1989). Located slightly further to the east on Rongerik Atoll were 28 American weathermen who were also exposed. About 20 h after the explosion the radioactive cloud reached Utrik Atoll, located to the east about 600 km from the detonation site, where 167 people were exposed to fallout that was not visible as it was on Rongelap, and that was substantially reduced in radioactivity compared to that at Rongelap.

Within about 54 h, the Marshallese were evacuated from Rongelap and Ailinginae; the Utrik population was evacuated within about 108 h (Cronkite et al. 1997; Simon 1997). The residents of Utrik returned to their atoll in June 1954. The residents of Rongelap Atoll were returned to their homeland in June 1957 and left again in 1985 due to continued fear of radioactive contamination. The 23 fishermen of the Lucky Dragon, their radiation exposure unbeknown to either United States or Japanese authorities, returned to their Japanese harbor after 14 d of navigation and were hospitalized in Tokyo suffering from various sequelae of acute radiation exposure (Conard 1980).

An assessment of the doses received by the Rongelap group was afforded by the collection of a community-pooled urine sample (Conard 1980; Lessard et al. 1985) and some ground and aerial exposure rate measurements. The doses received before evacuation were essentially due to external irradiation from short-lived radionuclides (with radioactive half-lives of up to a few days) present in the radioactive cloud or deposited on the ground, and to internal irradiation caused by the ingestion of short-lived radioiodines deposited on foodstuffs and on cooking utensils (Lessard et al. 1985). Thyroid doses, in particular, were very high because little decay of the fallout had taken place at the time of deposition—only a few hours after the detonation. Estimated thyroid doses at Rongelap ranged between 10 Gy for an adult and 50 Gy for a one-year old (Table 2). Estimated doses at Ailinginae were about one-third of that at Rongelap, and doses at Utrik were less than 20% of those received at Rongelap. The thyroid doses from ^{131}I that were received by the 23 Japanese fishermen of the vessel, Lucky Dragon, were estimated to range from 0.2 to 1.2 Gy (Conard 1980). Besides ^{131}I, other short-lived radioiodines contributed to the thyroid dose of the sailors. Assuming that the fishermen inhaled radioiodines for 5 h after the detonation, their total thyroid dose was estimated to have been about 0.8 to 4.5 Gy (Conard 1980).

The whole-body doses received by Marshallese living at Rongelap, Ailinginae, and Utrik and the United States weathermen servicemen were estimated by Sondhaus and Bond (1955) using data from film badges at the nearby atoll of Rongerik and from exposure rate measurements made using survey instruments. A later evaluation was made by Lessard et al. (1985) using those data and other measurements. The various estimates are in relatively good agreement. The external doses estimated by Lessard et al. (1985) were about 2 Gy at Rongelap, 1 Gy at Ailinginae and Rongerik, and about 0.1 Gy at Utrik.

The 23 Japanese fishermen of the fishing vessel, Lucky Dragon, were exposed to heavy fallout that was deposited over the entire boat and their bodies (Conard 1980). The doses from external irradiation due to radioactive materials deposited on the boat were estimated to range from about 1.7 to 6 Gy, depending on the individual's behavior and movements in the boat and the contamination of the cabin. Those doses were received during the 14 days separating the onset of fallout and their return to harbor; half or more of the external doses were received during the first day after the onset of fallout (Conard 1980).

Other atolls received varying but generally much lower exposures from the CASTLE series (Breslin and Cassidy 1955). The exposures from CASTLE received at southern atolls were 2,000 to 5,000 times less than that received on Rongelap Island. That comparison includes the effect of the evacuation that truncated the whole-body exposures of the Rongelap residents to about 45% of that that would have been received otherwise. We have estimated that the collective exposure from the 1954 CASTLE series was about 190 person-Gy (in a population of about 13,500). This estimate was made using the HASL exposure estimates for the CASTLE series reported by Breslin and Cassidy (1955) and the results of the 1958 census reported in 1988 (RMI 1989).

The evacuated populations received additional whole-body exposure from residual radioactivity after their return to their home atolls. Doses from external irradiation that were received up to 1979 by adults who returned to their islands in 1954 (Utrik) and 1957 (Rongelap) were estimated to amount to about 20 mGy for Rongelap and 30 mGy for Utrik (Conard 1980). The doses received after the Rongelap and Utrik people returned to live on their home islands were due to radionuclides with relatively long half-lives (principally ^{60}Co, ^{65}Zn, ^{90}Sr, and ^{137}Cs). Those doses were assessed on the basis of a large number of measurements on people and in the environment (Conard 1980). Some members of the Bikini community also received some exposure after they reinhabited the atoll between 1971 and 1978. Greenhouse et al. (1980) calculated the total whole-body doses received by the Bikini residents during those years to be 2 to 3 mSv y^{-1}.

Prospective (future) doses have also been estimated for populations that might return to live on Bikini, Enewetak, or Rongelap Atolls. Those dose assessments, conducted by Lawrence Livermore National Laboratory, rely on extensive radionuclide concentration data derived from analysis of food crops, ground water, cistern water, fish and other marine species, animals, air, and soil. Depending on the diet assumed to represent eating habits of the residents—which might range from consuming only locally grown food to various mixtures of local and imported food—future effective doses for a 70-y lifespan would be on the order of 150 (mixed diet) to 560 mSv (local food only diet) at Bikini Atoll (Robison et al. 1996), 54 to 115 mSv at Enewetak (Robison et al. 1987), and 10 to 20 mSv over a 70-y lifespan at Rongelap Atoll (Robison et al. 1994).

The effective doses from internal irradiation that are currently received in the remainder of the Marshall Islands were estimated by Simon and Graham (1994) to be, on average, less than 0.1 mSv y^{-1} for persons eating a diet of about 75% locally grown foods and 25% rice with no other imported food. Cumulative effective doses incurred between 1959 and 1994 would be, on average, less than 5 mSv (Simon and Graham 1994, 1997). Almost the entire effective dose is due to ^{137}Cs.

Semipalatinsk, Kazakhstan (USSR test site)

The Semipalatinsk Test Site (STS) was formerly a nuclear test site of the Soviet Union. The STS is situated in Kazakhstan in eastern Asia at a distance of about 200 km (southwest) from the border of the Russian region of Altai. The Soviet Union began atmospheric tests of nuclear devices at STS on 29 August 1949. During the period of nuclear weapons testing, 456 tests of nuclear devices were carried out there (Mikhailov 1997). Among those, there were 86 atmospheric tests and 30 surface tests. The last atmospheric test was conducted on 24 December 1962. The total energy yield of atmospheric nuclear explosions at STS was about 6.6 megatons (Dubasov et al. 1994[†]).

The main contributions to the local and regional environmental radioactive contamination are attributed to the atmospheric nuclear tests that were conducted on 29 August 1949 (22 KT), 24 September 1951 (38 KT), 12 August 1953 (400 KT), 16 March 1956 (14 KT), and 24 August 1956 (27 KT). These tests are estimated to have contributed more than 95% of the collective dose of the population living close to the STS (Dubasov et al. 1994[†]).

Doses received by the public from "local fallout" originating at the STS depend, in part, on the location of the village (Kazakhstan or Russia) and on the ethnic group or nationality of the inhabitants (Kazak or Russian). There are some dietary and lifestyle differences that apparently are important. Moreover, information on exposures of the public is scattered and located in a variety of documents from different Russian and Kazak research institutions with little effort to date towards making comparisons and resolving differences, uncertainties, and possible biases. Hence, dose estimates for the same locations sometimes vary depending on the origin of those estimates. Presumably, there may be differences in availability of monitoring information to some research groups, and possibly political biases that lead to those differences.

Presently, there are several groups of Russian experts that are actively involved in the reconstruction of doses received by the populations in the immediate region (Kazakhstan) and the nearby Altai region of Russia. The most important groups are those from the Moscow Institute of Biophysics (IBP) and from the Central Physical-Technical Institute of the Russian Ministry of Defense. Descriptions of the methodology of these various groups can be found in Loborev et al. (1994, 1995, 1997) and Gordeev et al. (1994, 1995a, 1995b, 1995c[‡]).

The IBP group currently collaborates with the U.S. National Cancer Institute (NCI) in an effort to estimate doses for the purposes of an epidemiologic study of thyroid disease. Researchers from the IBP have developed a detailed model for assessment of internal doses (Gordeev et al. 1994, 1995a, 1995b). In particular, that model determines the fraction of the deposited radioactive material which is of a particle size <50 μm and, hence, is available for retention on vegetation, intake by dairy animals, and available for inhalation. The IBP interception model is conceptually similar to that proposed by Simon (1990) but treats each test individually and in more detail. The model predictions for what is termed the "biologically available fraction" of fallout increase with distance towards an asymptotic value. Locations close to the test site are predicted to have relatively small ingestion and inhalation doses despite large external exposures because particle sizes at those locations were likely too large to be assimilated by animals and/or humans.

Doses received in Kazakhstan. Estimates of collective doses from external irradiation in the vicinity of the STS have been reported by Tsyb et al. (1990). According to them, the greatest collective doses were

[†] Dubasov Yu V, Krasilov GA, Logachev BA, Maltsev AL, Matushchenko AM, Safranov BG, Smagulov SG, Tsaturov Yu S, Fillipovskiy VI. Semipalatinsk and North Test Sites in the USSR. Integrated program of radiation and ecological researches on nuclear tests environmental consequences. Paper presented at the first SCOPE-RADTEST international workshop. Vienna, Austria; 10–14 January; 1994.

[‡] Gordeev KI, Ilyin LA, Kiselev VI, Lebedev AN, Savkin MN, Shoikhet Ya N. Application of an experimental-and-theoretical method for reconstructing probable doses of thyroid irradiation for the Altai population as a result of nuclear tests at Semipalatinsk Testing ground and initial results of using the method. Materials of SCOPE-Radtest Workshop; Liege, Belgium; 1995.

received in the administrative districts ("raions") of Abay (south of the test site) and Beskaragay (northwest of the test site) with lower doses at Semipalatinsk City. The total collective dose from external irradiation is estimated to have been about 2,600 person-Sv for the populations living in those raions (Tsyb et al. 1990). Radiation absorbed doses to the thyroid from both external and internal irradiation have been estimated to representative persons in various villages near the STS at distances ranging from a few tens of kilometers to about 350 km. Estimates of whole-body and organ doses depended on a variety of factors including village location (proximity), age, and lifestyle attributes which generally depended on ethnicity (Kazak, Russian, German, etc.). Table 2 provides representative whole-body and thyroid doses for seven villages, ranging from 0.2 to 900 mGy for whole-body dose (depending on village), and from 0.3 to 3.8 Gy for thyroid dose (Stepanov et al. 2001).

Doses received in Russia. An estimate of 41,200 person-Sv for the collective effective dose received in the Altai region of Russia has been reported (Shoikhet et al. 1999) though there has been little effort to date to independently verify this dose estimate.

According to Loborev et al. (1994), the nuclear explosion of 29 August 1949 produced the greatest impact on the Altai Region population. The collective dose for the Altai Region population from that test was reported to be 30,000 person-Sv (Djachenko et al. 1998).

Of the test sites discussed here, the STS probably has the most complex situation involving multiple investigators, multiple institutions, and at least two different political ideologies. Some documentation remains classified in Russia, which only serves to increase the difficulties of dose estimation and makes an independent evaluation of the dose and health impact on the public difficult and highly uncertain.

Nevada Test Site, USA (United States test site)

Located on the North American continent within the western United States, NTS was used for surface and above-ground nuclear testing from early-1951 through mid-1962. During the period of atmospheric testing, 86 tests were conducted at or above ground surface at the NTS, and do not include "safety" tests (UNSCEAR 2000; Back and Bennett 2002). The total energy yield of those explosions was approximately 1 MT of TNT-equivalent explosive energy. Most of the atmospheric releases of radioactive materials, including 5 EBq of ^{131}I and 6 PBq of ^{137}Cs, took place in test series conducted in 1951, 1952, 1953, 1955 and 1957.

In addition, approximately 800 tests, conducted underground since 1951, were designed for containment of radioactive debris; 38 of these had releases of radioactive materials that were small in comparison to those of the atmospheric tests, but sufficient to be detected by monitoring equipment located off-site (DOE 1994). Those tests are not discussed further in this paper.

Public concern began to surface in 1953, when several detonations of the UPSHOT-KNOTHOLE test series led to considerable fallout to the north and east of the test site, and the concern continued to build during the late 1950's and early 1960's (Church et al. 1990). Congressional hearings on the public health impacts of fallout were held in the late 1950's and early 1960's. By the late 1970's, hundreds of personal damage claims had been filed with the United States government alleging that illnesses, primarily cancers, resulted from nuclear testing activities at the NTS. The publication of one particular epidemiological study (Lyon et al. 1979) implied a causal relationship between radioactive fallout deposition and childhood leukemia. Those events and concerns prompted the need for a thorough re-evaluation of radiation exposures to the public from fallout produced by nuclear detonations at the NTS (Church et al. 1990; Whicker et al. 1996).

Consequently, four major dose-reconstruction studies related to the NTS were undertaken in the early 1980's: (1) the Off-Site Radiation Exposure Review Project (ORERP) study of the U.S. Department of Energy (DOE); (2) the Utah leukemia case-control study; (3) the Utah thyroid cohort study; and (4) the NCI fallout study. While the ORERP study evaluated doses from a variety of radionuclides and for a variety of body organs, the other studies concentrated on either bone marrow dose or thyroid absorbed dose. The first three studies were concerned with doses received by "local" populations (at locations less than 800 km from the NTS), while the fourth study dealt with the estimation of doses received across the continental United States. The second and third studies were conducted in the framework of epidemiological studies (Land 1996). In addition, a joint DHHS study was undertaken in 1999 to estimate doses possibly received across the United States from radionuclides other than ^{131}I and to organ sites other than thyroid. A report (DHHS) was completed in 2001.

The ORERP study of the Department of Energy. In 1979, DOE established the ORERP to produce a dosimetric re-evaluation of the off-site area characterized by region, community/locale, and age/occupation (Church et al. 1990).

A methodology was developed by the ORERP to reconstruct exposure rates using calculations of Hicks (1981, 1982). In addition, the deposition density (Bq m^{-2}) of individual radionuclides was estimated.

The efforts of the ORERP were divided into two phases which addressed exposures within the closest 300 km to the NTS, where ground-monitoring data was available (Phase I area), and, later, to the states of Arizona, New Mexico, Nevada, and Utah (excluding areas in the Phase I study region), southeastern California, western Colorado, southern Idaho, southeastern Oregon, and southwestern Wyoming (Phase II area). Deposition estimates were derived for many locations and assembled into databases for towns and counties. The manner in which the databases were developed has been described in detail by Beck (1996).

Doses from external irradiation were estimated stochastically (Henderson and Smale 1990) using Monte-Carlo techniques for nine age/occupation categories for each Phase I location/event combination in the Town Data Base and for each county/event combination in the County Data Base (Anspaugh et al. 1990). Doses from internal irradiation were estimated using the PATHWAY model (Whicker and Kirchner 1987), a dynamic model using site-specific data on agricultural, lifestyle, and environmental transport parameters (Kirchner et al. 1996; Whicker et al. 1996).

The Utah leukemia case-control study. The Utah leukemia case-control study, funded by NCI, was designed to test earlier observations (Lyon et al. 1979; Machado et al. 1987) that seemed to indicate an excess of childhood leukemia in southern Utah following atmospheric testing of nuclear weapons at NTS. Inclusion in the leukemia study, either as a case or as a control, was based on: (1) a date of birth prior to 1 November 1958, as listed in the records of the Church of Jesus Christ of Latter-Day Saints (LDS), and (2) a date of death between 1 January 1952 and 31 December 1981, as indicated on a Utah death certificate (Stevens et al. 1990; Simon et al. 1995). Cases consisted of all individuals who met these criteria and died of leukemia; 1,177 cases were identified. A control population of 5,330 subjects was selected randomly from deceased Utah residents and was matched by age, sex, and year of death.

The tissue of interest for leukemia is the active bone marrow. It was shown (Beck and Krey 1983) that when all pathways of exposure are considered, external irradiation from radionuclides deposited on the ground present by far the most important dose contribution to the active marrow. Hence, the Utah leukemia study assembled detailed residence histories of all study subjects using records made available by the LDS Church (Lloyd et al. 1990). The dosimetry methodology is described in Simon et al. (1995). The findings indicated a weak, not statistically significant association between bone-marrow dose and all types of leukemia (Stevens et al. 1990). The greatest excess risk was found in those individuals in the high-dose group with acute leukemia who were younger than 20 y at time of exposure and who died before 1964.

The Utah thyroid cohort study. The Utah thyroid cohort study, also funded by NCI, was a follow-up to a study conducted in 1965 to 1970 by the Bureau of Radiological Health, in which children living in Washington County, Utah, and Lincoln County, Nevada, had been examined for the presence of thyroid abnormalities, and children of Graham County, Arizona, had been used as a control group (Rallison et al. 1974). The Utah thyroid cohort study consisted of locating the same cohort of subjects identified in the 1965 to 1970 study and re-examining them for the presence of thyroid neoplasms and other thyroid disease. Altogether, doses were assigned for 3,545 subjects, of which 3,122 were re-examined (Till et al. 1995) using methods described in Simon et al. (1990).

Thyroid doses from NTS fallout were mainly due to the consumption of foodstuffs contaminated with ^{131}I, with other minor contributions from the consumption of foodstuffs contaminated with ^{133}I, from external irradiation from fallout radionuclides deposited on the ground, and from inhalation of air contaminated with both ^{131}I and ^{133}I.

The deposition estimates were obtained using the ORERP methodology and the two ORERP deposition databases, supplemented with additional information for other locations. Deposition estimates were ascertained for 5,804 locations of subject residences and/or locations of milk producers. The radionuclide concentrations in cows' milk, goats' milk, and leafy vegetables were obtained using a suite of models and data from a survey of dairy management practices (Simon et al. 1990).

The NCI fallout study. The NCI fallout study was carried out in response to Public Law 97-414 and consisted primarily of an assessment of the exposure of the American people in all 3,100 counties of the United States to ^{131}I originating from the NTS (Wachholz 1990). Thyroid doses were estimated for representative individuals in each county of the contiguous United States for each event at the NTS that resulted in significant fallout. Emphasis was placed on modeling the pasture-cow-milk food chain but also inhalation and ingestion of foodstuffs other than fresh cows' milk were included (Bouville et al. 1990). Some of the counties within the states of Nevada, California, Oregon, Idaho, Utah, and Arizona, were within what we consider to be the "local fallout" region.

Conceptually, the NCI study was similar to the ORERP study (as far as the estimation of thyroid doses from ^{131}I was concerned) and to the dosimetric effort related to the Utah thyroid cohort study. The primary difference between the three studies was that in the NCI fallout study, populations living in all counties across the contiguous United States were considered, whereas the other two studies dealt only with people residing in a few states in the vicinity of NTS. Furthermore, thyroid doses in the ORERP study and in the NCI fallout study were assessed for representative, unspecified individuals, whereas thyroid doses to identified individuals were estimated in the Utah thyroid cohort study.

The NCI study was especially detailed in reconstructing the deposition of ^{131}I across the United States for each significant event at NTS. Deposition data from the gummed-film network of the AEC Health and Safety Laboratory collected between 1951 and 1958 from the 40 to 95 monitoring sites located throughout the country at that time were used to calculate estimates of daily depositions of ^{131}I at those sites (Beck 1984; Beck et al. 1990). Depositions of ^{131}I at unmonitored locations were estimated by interpolation using precipitation data and appropriate statistical techniques, especially kriging (Gogolak et al. 1988). For locations in the vicinity of NTS, the ORERP deposition estimates were used directly.

The estimation of the exposure and thyroid doses received by the American people as a result of ^{131}I fallout from the NTS was reported in 1997 (NCI 1997) and can be found on the NCI internet site (**http://rex.nci.nih.gov/massmedia/Fallout/index.html**).

Doses received locally as a result of NTS fallout

Doses from external irradiation were estimated by the ORERP for the populations of the Phase I (Clark, Lincoln, Nye, and White Pine Counties in Nevada, and Washington and Iron Counties, Utah) and Phase II areas (Nevada, Utah, Arizona, New Mexico, eastern California, southeast Oregon, southern Idaho, southwest Wyoming, and western Colorado). ORERP dose estimates for the Phase I area were compiled and analyzed by Anspaugh and Church (1986) and by Anspaugh et al. (1990) to estimate the cumulative collective dose in those regions. The collective external whole body dose for the ORERP Phase I area was about 500 person-Gy (reported as 80,000 person-R including building shielding), the most important contributions being due to the test series of 1953 and 1955 (Anspaugh et al. 1990). Most of the individual doses received were less than 5 mGy and were essentially due to short-lived radionuclides (with a half-life of less than 100 d). The collective dose from external gamma sources reported for the ORERP Phase II area was 12,000 person-Gy (Anspaugh 2000).

Estimates of bone-marrow doses for the 6,507 study subjects of the Utah leukemia case-control study were also derived from the ORERP Town and County databases (Lloyd et al. 1990; Stevens et al. 1990; Simon et al. 1995). There was little difference in median (or mean) doses of cases compared to control subjects: 3.2 mGy (2.9 mGy) for cases compared to 3.1 mGy (2.7 mGy) for controls (Simon et al. 1995). The maximum estimated doses were 26 and 29 mGy for cases and for controls, respectively. The minimum doses were zero, as it was assumed that people who lived outside of the domain considered (i.e., part or all of Utah, Nevada, Idaho, Wyoming, Colorado, New Mexico, and Arizona) during the period of intensive fallout (from 1951 to 1958) received no dose from NTS fallout.

Doses from internal irradiation within the "local fallout" area were mainly due to inhalation of radionuclides in air and to ingestion of foodstuffs contaminated with radioactive materials. As far as local fallout is concerned, doses from internal irradiation were, for most organs and tissues, substantially smaller than those from external irradiation. The notable exception was the dose to the thyroid from internal irradiation, which was much higher than both the dose from external irradiation and the doses from internal irradiation to other organs and tissues (Whicker et al. 1996).

Doses to the thyroid from NTS fallout received by the populations living in the downwind counties from the NTS have received substantial attention. For example, estimates were made in the early- and late-1960's as well as in the 1990's (Anspaugh et al. 1990). The earliest estimates to representative persons, derived from relatively meager information, were in relatively good agreement with those produced later: 660 mGy (Mays 1963) and 500 mGy (DHHS 2001). Dose estimates to members of the Utah thyroid cohort were reported in Till et al. (1995) and Simon (1999). Overall mean thyroid dose for the cohort studied was 98 mGy, with a median dose of 25 mGy. The maximum calculated thyroid dose for any subject was 4,600 mGy.

The importance of the contribution of the consumption of milk to the thyroid dose is worth noting. The mean dose among the subjects in the Utah thyroid study who did not drink milk was 12 mGy, while the mean dose among the subjects who drank milk was 100 mGy. Of particular importance are the 155 subjects who drank goat's milk at some point in their childhood. The mean dose among this group was 300 mGy, and the highest dose (4,600 mGy) was found for an individual in that group. Five subjects received an absorbed thyroid dose greater than 3,000 mGy; all of them drank milk from a family owned goat (Till et al. 1995).

Emu Field, Maralinga, and Monte Bello Islands, Australia (United Kingdom test site)

Located on the continent of Australia, the test sites at the Monte Bello Islands, Emu Field, and Maralinga were used for testing nuclear devices by the United Kingdom beginning in 1952. Twelve tests of nuclear weapons were conducted by the British in Australia in five series from 1952 through 1957. In October 1952, a test of the Hurricane series was conducted, including one on a ship in the Monte Bello Islands (off the coast of Western Australia). In October 1953, the two tests of the series Totem were carried out at Emu Field, South Australia. In May–June 1956, the two tests of the series Mosaic were detonated on Monte Bello Island, and four more tests were conducted in the Buffalo series in September–October 1956 at Maralinga, South Australia. Finally, in September–October 1957, the three tests of the Antler series were detonated at Maralinga. The yield of these tests varied from 1 to 60 KT of TNT-equivalent; the total energy yield of those 12 tests was less than 0.2 megaton of TNT-equivalent (Wise and Moroney 1985).

Estimates of doses to representative persons have been made for local population centers as well as for population centers throughout Australia (Wise and Moroney 1985). For the nine nuclear tests of the Mosaic, Buffalo and Antler series, the primary radiation monitoring data available to estimate the doses were total beta-activities of radionuclides in fallout deposition and in air from Australia-wide monitoring programs (Butement et al. 1957, 1958; Dwyer et al. 1957). In addition, for all 12 nuclear tests, trajectories of the radioactive clouds across Australia and meteorological data were available (Gale 1954; Gale and Crooks 1954; Peirson 1955; Butement et al. 1957; Phillpot 1957, 1959). For the seven tests of Buffalo and Antler, external dose rate and total beta activity of radionuclides in fallout and in air within the region of close-in fallout (Carter 1957; Clay 1957; Cater 1958) were available. For the two tests of Totem, airborne radiation survey data of ground contamination (Cambray and Munnock 1954) were available.

For the three tests of Hurricane and Mosaic, ground contamination of the nearby coastal region of the mainland and of distant population centers is known (Gale and Crooks 1954; Matthewman 1957).

Estimates of external doses from local fallout are not available for the Hurricane, Totem, and Mosaic series of 1952, 1953, and 1956, respectively. External doses for the Buffalo and Antler series (1956 and 1957, respectively) were estimated from the local measurements of exposure rate and fallout deposition, assuming that the external dose rate varied as a power function of time. The whole-body doses from external irradiation are estimated to have been less than 1 mGy in all local population centers that were monitored.

The number of distant population centers that were monitored was 85 for Buffalo and Antler series and 29 for Mosaic. Estimates of external doses are available for each monitored population center and for each test of the three series. External doses for the series Hurricane and Totem were estimated by scaling the results from similar nuclear tests of the series Mosaic, Buffalo, and Antler according to the known yields of the explosions. The average effective dose equivalents from external irradiation to the Australian population were found to be quite low: 0.0011 for Mosaic, 0.0041 for Buffalo, and 0.0031 mSv for Antler (Wise and Moroney 1985). The collective effective dose equivalent was reported to be about 700 person-Sv, similar in magnitude to the value for the immediate area near NTS (ORERP Phase I area).

Standard models of environmental transfer in air, and to drinking water and foodstuffs were also used (Wise and Moroney 1985). It was found that internal irradiation accounted, on average, for 83% of the total effective dose equivalent. The average individual effective dose equivalent for all tests conducted in Australia was estimated to be 0.07 mSv.

Novaya Zemlya and Kapustin Yar, Russia (Soviet Union test site)

Located at the very easternmost edge of Europe were the Soviet test sites on Novaya Zemlya (islands) and at Kapustin Yar. Testing began at Novaya Zemlya in 1955 and at Kapustin Yar in 1957. Novaya Zemlya, the northern nuclear test site of the Soviet Union, was located on a group of islands off the northwestern coast of Russia between the Barents and Kara Seas, and south of the Arctic Ocean. Novaya Zemlya, meaning "new land," consists of two large islands, Severny (northern) and Yuzhny (southern), aligned for about 1,000 km in a southwest-northeast direction, plus several smaller islands. The two major islands are separated by a narrow strait less than 3 km wide. The island group has an area of 82,600 square km (31,900 square miles). Novaya Zemlya is for the most part mountainous. More than one-quarter of the land area, especially in the north, is permanently covered by ice. The climate is severe: cold and often foggy and windy. The vegetation on those portions of the islands free from ice is predominantly low-lying tundra with much swampland in valleys. The first nuclear weapons test at Novaya Zemlya was an underwater test of 3.5 KT conducted on 21 September 1955, while the last atmospheric test was on 25 December 1962 (Andryshin et al. 1996). Novaya Zemlya was the site of the world's largest nuclear weapons test, a 50 MT detonation at an altitude of about 3.5 km on 30 October 1961. In all, 91 atmospheric nuclear tests took place at Novaya Zemlya, with a total explosive yield of 240 megatons (UNSCEAR 2000).

The nuclear tests conducted on the Novaya Zemlya islands accounted for about half of the total energy yield of all nuclear tests carried out worldwide; however, there is very little available information on local or regional doses resulting from those tests. It is likely, however, that the local doses to offsite residents were relatively small, because most of the atmospheric devices were exploded at high altitude so that the expanding fireballs did not touch the ground surface. Only one test was conducted directly on the ground surface, a 32 KT detonation on 7 September 1957. There were also 17 underground tests that vented, resulting, in most cases, in onsite contamination only (Dubasov et al. 1994†). The nearest village, Amderma, is 280 km away. The much larger population center of Arkhangelsk is approximately 1,000 km away, and three villages lie at intermediate distances (IPPNW 1991).

Current exposure rates in the Novaya Zemlya islands vary generally from 8 to 12 μR h^{-1}, which is similar to the range observed in adjacent areas not used for testing and represents essentially natural background (Dubasov et al. 1994†). However, much higher exposure rates can be measured in small areas (Dubasov et al. 1994†).

No information has been found on doses from external irradiation in offsite areas. However, it is known that ^{137}Cs is abundant in lichen, reindeer, and other environmental media (Dubasov et al. 1994†). The ^{137}Cs concentrations in reindeer meat are much greater than those in milk, fish, geese or ducks. Therefore, people like reindeer herders, who use reindeer meat as a staple food, likely received much higher internal doses than the urban residents in the area who consume reindeer meat only occasionally. It is estimated that the reindeer breeders received internal effective dose rates from ^{137}Cs and, to a smaller degree from ^{90}Sr, of 1 mSv y^{-1} on average since the early 1960's (Ramzaev et al. 1993); the dose rates to urban residents, in contrast, are estimated to have been about 100 times lower (Ramzaev et al. 1993).

Nearly nothing is known—at least in western literature—about exposures from the nuclear tests launched from Kasputin Yar. All the Kapustin Yar tests were high-altitude explosions with a total explosive yield of about 1 MT TNT equivalent. In general, high-altitude tests contribute more to "global fallout" than to "local fallout." Hence, it is not expected that locally resident populations received substantial exposures.

Christmas Island and Malden Island, Kiribati (United States and United Kingdom test sites)

Located in Oceania, Christmas and Malden Islands were used by both the United States and the United

Kingdom for testing nuclear devices. Testing began on Christmas and Malden Islands in 1957. Both islands are now part of the Republic of Kiribati.

Christmas Island was annexed by Great Britain in 1888 and was a United States air base during World War II. It served as a base for British nuclear tests in 1957–1958 and for United States nuclear tests in 1962. The land area is about 390 km^2, and the 1990 population was about 2,500. Nearby Malden Island is a flat, triangular atoll, measuring 6 by 8 km that encloses a small lagoon. The atoll is uninhabited today, as it has been since the occupation by British nuclear scientists between 1956 and 1962.

The British conducted 6 nuclear tests at Christmas Island and 3 near Malden Island with a total yield of about 7.9 MT. The Grapple 1/Short Granite test of 15 May 1957, which yielded between 200 and 300 KT, was an airdrop and was Britain's first test of a implosion thermonuclear bomb design (FAS 2001). There were also 24 nuclear tests conducted by the United States in the vicinity of Christmas Island with a yield of about 23 MT.

There is little or no information available on exposures of the public or of civilian test personnel at Christmas and Malden Island, although United Kingdom, New Zealand, and Fijian veterans of those tests have reported many types of medical problems that they believe were caused by radiation exposures from the tests. Recently, a study interviewed 10% of the test veterans, and after correcting for biases of sampling, the author claimed more than a two-fold increase in cancer incidence (Tattam 1998). In 1999, the British government rejected compensation claims by Fijian veterans who served during the British nuclear weapons tests at Christmas and Malden Islands in the late 1950's. A primary issue of contention is whether protective clothing was issued to everyone on the island during the tests and to those involved in clean up operations afterwards. Claims are that Fijian troops, unlike some of their British and New Zealand counterparts, were not given proper protective clothing.

Johnston Island, USA (United States test site)

The United States used Johnston Atoll as a launch site for high-altitude nuclear tests beginning in 1958. Johnston Atoll is an unincorporated territory of the United States and is located about 1,330 km (720 nautical miles) SW of Honolulu, Hawaii. It has been for several decades, and remains today, a U.S. military installation and wildlife sanctuary. Twelve nuclear tests with a combined yield of about 21 MT were conducted in the area near Johnston Atoll. The tests near Johnson Atoll were all intended as airbursts.

Of the 12 tests, 3 resulted in unintended non-nuclear destruction that led to contamination of the atoll with radioactive debris. The Starfish device (19 June 1962) was aborted at 30,000 feet, Bluegill Prime (25 June 1962) was aborted on the launch pad in a large fiery explosion, and Double Prime (15 October 1962) was aborted at 109,000 feet. The aborts of these tests involved destruction of the missile and nuclear weapon with high explosive. The contamination resulting from these incidents was primarily in the form of particulate debris, much of it being metal from the rocket accompanied by considerable amounts of fissionable plutonium and/or uranium. The deposition of radioactive debris from these unintended non-nuclear detonations can be considered as "local fallout."

There is no evidence of native populations ever living on the atoll and certainly none were present during the years of nuclear testing. Hence, there is no evidence that members of the public within the immediate region were exposed to "local fallout" originating at Johnston Atoll. The closest populated islands would have been those of Hawaii. However, the nine successful nuclear tests, because of their large yields and high altitude of detonation, would have contributed to global fallout.

Reggane, Algeria (French test site)

Located in Algeria on the African continent were two nuclear test sites of France. Between 1960 and 1966, France conducted a series of above-ground and underground nuclear tests at Reggane and In-Ekker, both remote sites located in the south of Algeria. There were four atmospheric and 13 underground tests conducted by the French in Algeria (UNSCEAR 2000).

The Reggane test site is located in the Sahara desert, about 50 km southeast of Reggane, a village/oasis of a few thousand inhabitants and about 150 km south of Adrar, a city with approximately 50,000 inhabitants. Though the Reggane site is presently not sealed off, access to the area of the test sites has been, and continues to be, restricted by military control. There are practically no roads leading to the Algerian test sites, making access very difficult.

Four atmospheric tests named "Gerboise" (Bleue, Blanche, Rouge, and Verte) were undertaken in 1960 and 1961 in the CSEM (Centre Saharien d'Expérimentations Militaires–Saharan Military Test Centre) set up around the Reggane Oasis. Three of the atmospheric tests were carried out on a tower, while Gerboise Blanche was performed on the ground. The total yield released in the four tests was between 70 and 120 KT TNT equivalent.

No information has been found on estimated doses to the public from the atmospheric nuclear tests conducted by France in Algeria. In the absence of official documentation, however, there has been considerable speculation and rumor about exposures of test personnel as well as Algerians. For example, it is claimed that the second test at In-Ekker, code-named Beryl, exploded on 1 May 1962, was tested under adverse wind conditions and against the advice of the Commission of Nuclear Safety. Consequently, 12 soldiers were contaminated when radioactive vapor escaped through a fissure in the rock; nine of them are alleged to have received more than 1 Sv (May 1989; IPPNW 1991).

Lop Nor, China (Chinese test site)

Located in central Asia, the Lop Nor test site was used by the People's Republic of China to test nuclear devices beginning in 1964. Lop Nor is located in a vast desert location in western China. The first Chinese-made atom bomb (a fission device) was tested there on 16 October 1964; the first guided missile-launched device on 27 October 1966; and the first thermonuclear (fusion) test on 28 December 1966. The Chinese had an accelerated program to transition their nuclear devices into weapons. The second Chinese test (14 May 1965) was a test of a bomber-delivered weapon. The fourth test was of a missile warhead.

The third and fifth Chinese nuclear explosions were experiments to test the properties of thermonuclear materials, principally lithium-6 deuteride, and clearly benefited from knowledge of the Soviet and American weapons programs. Those tests were "boosted" fission weapons; fusion fuel was placed in the core of an implosion fission weapon. The yields of these weapons were on the order of several hundred kilotons.

It took the Chinese only six tests to arrive at a true thermonuclear weapon. On 17 June 1967, a medium-range bomber dropped a bomb over Lop Nor, which detonated as a 3 MT explosion. The rapid development of the Chinese hydrogen bomb is even more remarkable when one considers the political turmoil in China at the time (Lewis and Litai 1988).

China conducted 34 nuclear weapons tests between 1964 and 1988; of these, 22 were atmospheric tests and the others underground (IPPNW 1991; De Geer 1996§; Liu and Zhu 1996**). The total explosive yield of the 22 atmospheric tests was about 21 MT.

Little information is available on doses received by the public or by test personnel in China. It is known, however, that for each test, the trajectory of the cloud carrying the radioactive debris was determined. In addition, a nationwide monitoring network for environmental radioactivity of 45 stations was set up in the early 1960's by the Ministry of Public Health (Zhu et al. 1994††). Monitoring data include the deposition densities of important fallout radionuclides and radionuclide concentrations in air, drinking water, and in foodstuffs (China 1990, 1995). Doses have been estimated from the measured environmental levels using ICRP and UNSCEAR models (Ye 1994‡‡; Zhu et al. 1994††; Liu and Zhu 1996**).

The absorbed doses in air measured outdoors in several population centers located downwind from the test site were reported by Zheng et al. (1996§§; see Table 2 of this paper). The measured doses, which include exposures resulting from all important Chinese tests, have been compared with predicted values obtained using an atmospheric transport and deposition model (Zheng et al. 1996§§). A reasonable agreement between measured and predicted values was obtained for most locations. The average absorbed dose in outdoor air was 0.18 mGy; assuming that people spent, on average, 80% of their time indoors, where the shielding afforded by the building reduced the exposure rate to 20% of that outdoors. A mean effective dose of 0.044 mSv was estimated for the populations living downwind of the Lop Nor nuclear test site at distances ranging between 400 and 800 km.

Dispersion of ^{131}I from the tests has been reported by Liu and Zhu (1996**). The adult thyroid dose estimates range from 0.06 mGy in Taiyuan to 2.5 mGy in Lanzhou; thyroid doses to infants would have been about 10 times higher. The average thyroid dose received by the Chinese population as a result of the tests conducted at Lop Nor was estimated to be about 0.14 mGy (Liu and Zhu 1996**).

The long-lived fission products ^{90}Sr and ^{137}Cs have been monitored throughout China since the early 1960's though the data are generally inaccessible by westerners. Even though the average deposition density of ^{90}Sr seems to be have been lower in China than in the remainder of the northern hemisphere, the internal doses from ^{90}Sr are estimated to be higher in China. This anomaly is explained by the fact that the Chinese diet is not typical of that of the populations of the northern hemisphere (Liu and Zhu 1996**). The average effective dose resulting from the intake of ^{90}Sr was estimated to be 0.27 mSv (Zhu et al. 1994††). Most of this effective dose was due to tests that were not conducted on Chinese soil.

The Lop Nor test site, while never having been opened to western scientists, has been the subject of recent international conservation efforts. In 1999 it was announced that international funding had enabled the Lop Nor nuclear test site to be set aside as a reserve for the highly endangered Bactrian camel (BBC 2000), a species that some claim barely survived the nuclear testing conducted there.

Mururoa and Fangataufa, French Polynesia (French test site)

Located in Oceania, the atolls of Mururoa and Fangataufa, French Polynesia, were the last major atmospheric test sites to become operational. The two atolls were the sites of atmospheric nuclear testing, conducted by France, beginning in 1966 and continuing into 1974 (Doury and Musa 1996***). Mururoa Atoll, located at the southeastern tip of the Tuamotu Archipelago, French Polynesia is about 1,125 km (700 miles) southeast of Tahiti. Formerly uninhabited and used to grow coconuts, the atoll was ceded to France in 1964. French Polynesia

§ De Geer L-E. Chinese atmospheric nuclear explosions from a Swedish horizon. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 1996.

** Liu Y, Zhu C. Environmental contamination and health effect from iodine-131 in fallout in China. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 19–21 October 1996.

†† Zhu C, Liu Y, Zhu G, Gu Z. Radioactive contamination from nuclear fallout and health evaluation in China. Paper presented at the first SCOPE-RADTEST international workshop. Vienna, Austria; 1994.

‡‡ Ye C. Assessment of internal radiation dose from the fallout of nuclear explosions. Paper presented at the first SCOPE-RADTEST international workshop. Vienna, Austria; 1994.

§§ Zheng Y, Yongze M, Jiangchen L. Long range atmospheric transportation and fallout of nuclear test debris. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 1996.

*** Doury A, Musa C. The French part in atmospheric nuclear tests and their consequences. Paper presented at the fourth SCOPE-RADTEST international workshop. Beijing, China; 19–21 October 1996.

was selected as a new test site after Algeria because of the pending independence of that country and because only 5,000 inhabitants lived within a 1,000 km radius of the planned ground zero in Mururoa (IPPNW 1991).

Forty-six tests were conducted above ground (four at Fangataufa and 42 at Mururoa), including five safety-trials. The actual number of nuclear explosions was 41 (Bennett et al. 2000), including 37 at Mururoa and 4 at Fangataufa. Most of the devices were suspended from a balloon at a considerable elevation above the ground or water. There were also 137 underground tests (beneath the lagoon floor), 127 at Mururoa, and 10 at Fangataufa, which were conducted by lowering the explosive devices into holes drilled into the rock beneath either the rim or the lagoon of the atolls. There were 15 safety trials in all, 5 conducted in the atmosphere and 10 underground. The total explosive yield of the nuclear detonations was approximately 10 MT TNT equivalent (Doury and Musa 1996***).

Annual reports on the radiological situation in populated atolls and islands around Mururoa and Fangataufa were communicated to the United Nations. Radiological monitoring has been carried out on a limited number of islands deemed to be representative of the large archipelagos or groups of islands: (1) Tahiti (110,000 inhabitants) for the Society Islands, located at more than 1,000 km away from Mururoa and Fangataufa, (2) Tureia Atoll (140 inhabitants), the population center in the Tuamotu archipelago that is the closest (120 km) to the test site, (3) Hao (1,100 inhabitants), also in the Tuamotu archipelago, (4) Mangareva (600 inhabitants) for the Gambier Islands, (5) Tubuai (1,700 inhabitants) for the Tubuai archipelago, and (6) Nuku Hiva (1,800 inhabitants) and Hiva Oa (1,500 inhabitants) for the Marquise Islands (RF 1984). Doses have been assessed on the basis of radiation measurements in the terrestrial and the marine environments for the selected islands. Although occasional venting may have occurred following the underground tests conducted on or after 1975 (IPPNW 1991), it does not seem to have led to a detectable increase in the exposure rates or in the radionuclide concentrations in foodstuffs (RF 1984). This implies that annual doses have generally decreased since the mid-1970's.

Doses from external irradiation in Tahiti in July 1974 were about 0.6 mGy (UNSCEAR 1977, Bouville et al. 2000). In later years, the external doses were much lower; the effective dose rates ranged between 1 and 10 $\mu Sv\ y^{-1}$ in 1982 (RF 1984) and were estimated to be less than 4 $\mu Sv\ y^{-1}$ in 1995 (RF 1995). The average thyroid dose to infants in Tahiti in July 1974 was about 7 mGy (UNSCEAR 1977; Bouville et al. 2000). The effective dose rates from internal irradiation were estimated to be very low in later years, ranging from 2 to 32 $\mu Sv\ y^{-1}$ in 1982 (RF 1984) and to be even lower in the early 1990's (RF 1993, 1995, 1996). Table 2 partially summarizes the dose estimates for the populations of various atolls and islands of French Polynesia in 1982 (RF 1984). As in the Marshall Islands, most of the dose in years following the tests has been due to the presence of residual ^{137}Cs in the environment that originated in global fallout from tests at other locations. The collective effective dose for the populations of French Polynesia was estimated to have been about 1 person-Sv in 1982.

Even though doses were not reported before 1982, estimates can be derived from reported radionuclide concentration measurements in foodstuffs. For example, the thyroid doses due to the contamination of milk by ^{131}I in Tahiti have been calculated by the UNSCEAR (1977) for most years during the atmospheric testing period; the highest annual thyroid doses to infants were estimated to have been about 7 mGy and to have occurred in 1974.

In 1998, the International Atomic Energy Agency completed an extensive assessment of the present day radiological situation at Mururoa and Fangataufa (IAEA 1998) based on sampling, in situ and laboratory measurements, and groundwater and geological analysis by various international experts. It was concluded that no real population would likely receive in the future a dose greater than 1% of the background radiation dose as a result of present-day residual contamination at the site.

DISCUSSION AND CONCLUDING REMARKS

The reports reviewed here indicate a wide disparity in the quantity and quality of information available on exposures of the public living near each of the mentioned test sites. The availability of information appears partly related to the differences in political ideologies of the nations involved, as the degree of openness of government and military authorities varies widely among countries with nuclear capabilities. In general, the sites where nuclear testing began earliest (1946 to 1953: Marshall Islands, Semipalatinsk, NTS, and Australia, see top panel Fig. 1) have the most information available about exposures to the public. Part of the need for that information came about because the most serious exposures occurred from testing programs at those locations.

The case of the NTS, however, is somewhat unique. Testing of nuclear devices there benefited from experience gained in the Pacific at Bikini and Enewetak. Hence, there were no large individual exposures near the NTS as occurred in the Marshall Islands following test BRAVO. Moreover, tests at the NTS were all relatively small compared to the large Pacific tests. The impact of the NTS was different, however, because of the large population residing in the United States downwind of the test site. Hence, the collective external dose in the continental United States greatly exceeded that in the Marshall Islands: about 84,000 person-Gy in the U.S. compared to about 200 person-Gy in the Marshall Islands. Another unique aspect of the NTS has been the response of the United States government to the public's demand for information. Unlike that for any other nuclear test site worldwide, the United States government has made large amounts of information available through archives of historical documents, and little remains classified today that is not directly related to design of the weapons.

The test sites that were made operational from 1957 to 1962 (middle panel of Fig. 1: Novaya Zemlya, Kapustin Yar, Christmas and Malden Island, Johnston Island, and Reggane) had numerous large tests, though many of those were at high altitude or conducted in very remote locations. For those reasons, exposures from "local fallout" were probably not great, although there is very little, if any, information to confirm that.

The test sites that became operational last (1964 and 1966, bottom panel of Fig. 1: Lop Nor and French Polynesia) were relatively small in terms of total explosive yield. Both were located in relatively remote locations, though there were inhabited islands (Polynesia) or villages/small cities (China) at distances that could be considered to be within the area potentially susceptible to "local fallout." Nevertheless, the information available indicates relatively minor population exposures from those sites.

The number of tests and the related explosive yields conducted at the 16 nuclear testing sites are normally partitioned for discussion purposes by country that conducted the testing. However, other schemes may be equally or more informative, particularly for determining the regional collective dose and related public health impacts. For example, grouping nuclear tests by the continent on which they were conducted, regardless of the country responsible for the tests, may be useful because of similarities in the environment, climatic zone, and, possibly, lifestyle of the inhabitants. For example, the Semipalatinsk and Lop Nor test sites were both in the steppe/desert environment of mid-Asia and were the home of various groups of nomadic people that were highly dependent on grazing animals. The sites of Bikini/Enewetak, Christmas/Malden, Johnston, and Mururoa/Fangataufa were all coral atolls, typical of the tropical mid- and south-Pacific islands. Inhabitants of all the Pacific test sites would have had similar diets and lifestyles, particularly 50 years ago.

A summary of number of tests and yields by year of testing, continent where the testing was conducted, country responsible for the testing, and environment type/climatic zone is presented in Table 1. That table provides information useful for discussion from these various viewpoints.

The information in Table 1 indicates that there was one primary nuclear testing site in North America (Nevada) and except for Africa and Australia that test site had the smallest explosive yield (~1 MT at NTS compared to 0.2 MT in Australia and 0.1 MT in Africa). However, the number and density of people in the United States in the region of "local fallout" was probably greatest for any of the test sites.

In Australia and Oceania there were numerous islands used for nuclear testing; they can be grouped into five distinct locations: Marshall Islands, Johnston Island, Christmas/Malden, French Polynesia, and three locations in Australia. Several of these islands were uninhabited (Johnston, Christmas, and Malden Island) during the testing or had populations removed for the duration of the testing (Bikini and Enewetak). One major exposure incident took place in the Marshall Islands, when inhabited atolls to the east of the BRAVO detonation site were contaminated. The atolls used for testing in French Polynesia had never been inhabited, and although other atolls in the archipelago did contain resident populations at the time, they were relatively few and distantly located. The testing conducted in Australia was primarily in remote desert locations, uninhabited by any large populations, but containing a small resident indigenous population. The Monte Bello Islands used sparsely for testing in Australia were also uninhabited. The African, European, and Asian test sites were all continentally based and except for the test site in Kazakhstan, were relatively remote from any population centers. The northern test site of the Soviet Union (Novaya Zemlya) was virtually uninhabited and at substantial distance from any population center. The sites at Kapustin Yar, Russia, and Semipalatinsk, Kazakhstan—as in the Marshall Islands—had small populated villages in the region.

The nuclear test sites, if grouped by type of local environment or climate type, fall into four general categories: desert, tropical, arctic tundra, and steppe. The test sites in Nevada, Australia, Algeria, and China were all inland desert regions that tended to minimize the contamination of arable land and the likelihood that regional populations might be exposed. In general, there were few large population centers near the test sites. Some exceptions were Las Vegas, Nevada, and Semipalatinsk, Kazakhstan. Although there is no evidence that even moderate exposures were received in Las Vegas, one publication (Takada et al. 1999) claims that external doses up to 1 Gy were received by residents of Semipalatinsk. However, those claims were based on limited thermoluminescent dosimeter measurements in brick and have not been independently verified. The test sites located in the Marshall Islands, Johnston Island, Christmas and Malden Island, and French Polynesia were all tropical, island environments. The range of weather conditions in the tropics varies from drought, sometimes lasting for months, to episodic but intense rainfall. The soil in such environments is typically low in nutrients and high in moisture, thus allowing for significant uptake of residual radioactivity in plants. The coral reef environment is relatively fragile and subject to destruction from the testing.

The test site in Kazakhstan is an environment type between the desert conditions and those of the tropics: a steppe environment that is generally a low-altitude, semi-arid plateau, with extremely variable temperature and rainfall. The steppe in Kazakhstan is primarily a short grass prairie with low to moderate annual rainfall rates. The local environs are used to raise a variety of dairy animals, and the populations are highly dependent on those food products.

Finally, the test site at Novaya Zemlya, while also an island, is a cold, windy, and harsh environment, with the land under frost for much of the year. Although large weapons were tested there, few residents lived in the vicinity.

The highest exposures from any single test event were likely received by small numbers of people on Rongelap and Ailinginae Atolls in the Marshall Islands following the BRAVO test (at Rongelap: ~2 Gy external dose and 2 to 50 Gy to the thyroid, depending on age at exposure; at Ailinginae: about one-third the doses at Rongelap). There are no other reports of doses of similar magnitudes received anywhere. Several villages in the vicinity of STS likely received doses large enough to be detected by epidemiological investigation (200 to 1,000 mGy external, 500 to 6,000 mGy to the thyroid), although present information indicates that on average they were about an order of magnitude less than that received at Rongelap and more similar in magnitude to those received on Utrik Atoll in the Marshall Islands. There are minimal accounts of exposures received, with little factual evidence, following tests in French Polynesia and Australia. There is little or no information on exposures or doses received by the public following tests at Johnston Island (United States), Christmas and Malden Islands (Kiribati), Reggane (Algeria), and Novaya Zemlya and Kapustin Yar (Russia).

In terms of availability of quantitative estimates of exposure and dose received by local populations and by individuals, the NTS is easily the best documented site (DHHS 2001). Although some feel that the political system in the United States discourages examination of the consequences of the Cold War, more information about fallout and its consequences has been made public in this country than anywhere else. Possibly the test site with the next largest attempt to reconstruct doses is Semipalatinsk. But unlike the case for NTS, the information there is not readily available to all scientists, is distributed among many Russian documents and institutions with some documents still classified, and dose estimates by one set of investigators often differ substantially from estimates made by other regional institutions.

In closing, it is worthwhile to consider the degree to which the subject of exposures of populations to radioactive fallout has been adequately researched and the problems that might be faced in conducting further investigation. The quality of the available information on doses received by the public varies tremendously among the various nuclear testing sites around the world. Some reasons for inadequate information being available to the worldwide scientific community is that relevant documents remain classified in some countries; elsewhere there may be inadequate expertise available to estimate doses, or, in some countries, the issue of fallout-related doses and potential health effects is not a priority and does not receive research funding. In addition to the lack of availability of documents from some countries, it should also be noted that in the near future there may be a worldwide loss of information related to fallout simply for lack of space for archiving documents and/or improper care. This conclusion was reached in the joint DHHS feasibility study (DHHS 2001). Much of the documentation, which generally was of very limited distribution, is held within aging government agencies (worldwide) that are often under pressure to reutilize space. The value of fallout-related information in the future cannot be easily estimated, but it seems apparent that proper archival of historical documents related to public health and the environment will continue to have an importance. Hence, there should be consideration given to the idea that national or international agencies should establish a document archive for fallout related information and to maintain it in a centrally and universally accessible location. Without the documentation to determine legitimate estimates of collective dose near each site, it is difficult to assess the true local, as well as international, health impacts.

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